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Investigations of the Echoes In the Auditorium of the University of Illinois

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INVESTIGATION OF THE ECHOES IN THE AUDITORIUM OF THE UNIVERSITY OF ILLINOIS

BY

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A. B. University of Cincinnati, 1907

THESIS

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

OTTO STUHLMANN, JR.

ENTITLED INVESTIGATION OF THE ECHOES IN THE AUDITORIUM OF THE UNIVERSITY OF ILLINOIS

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF Master of Arts in Physics

F. R. Watson
In Charge of Major Work

A. P. Carman
Head of Department

Recommendation concurred in:

Committee on Final Examination

This is a problem which science has treated but sparingly. Rayleigh in his excellent treatise on sound points out that there are many points which still remain obscure, and which need investigation. Architects have pronounced the problem unsolvable, because of the many varying conditions that present themselves. Much remains to be done therefore, before a complete solution is given for the action of sound in a building.

The University Auditorium, because of its unfortunate acoustic defects, presents an opportunity to the physicist to investigate some of the laws of sound. The writer has thought it profitable to take advantage of this opportunity to study the action of sound in producing echoes, and also to suggest and try methods for curing the same.

If a source of sound is placed in a room it sends out energy in the form of longitudinal compressional waves requiring the air as a medium for their propagation. These waves move with a velocity of about 1100 feet a second and would by successive reflection fill a hall with sound in a fraction of a second.

In meeting an object, sound is reflected in accordance with the laws of light, making the angle of incidence equal to the angle of reflection. It is on the law of propagation and reflection of sound that the philosophy of echo depends as J. Henry[1] in the earliest work on this subject points out.

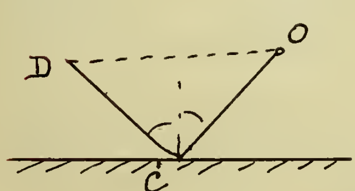
1 - Ann. Rep. Smith. Inst., p. 221, 1856.

He was the first to show that an echo was heard when the reflecting surface was outside of the "LIMIT OF PERCEPTIBILITY" in terms of space.

The limit of perceptibility may be defined as the shortest time that can elapse between two successive sounds, so that the ear detects no overlapping of the pulses. In his experiments on this subject he used a wall as a reflector and found that the limit of the distance was 30 feet, varying slightly, perhaps, with the intensity of the sound and the acuteness of different ears. This will give about the sixteenth part of a second as the limit of time necessary for the ear to separately distinguish two similar sounds. From this experiment we learn that the reflected sounds may tend to strengthen the impression, or to confuse it, according as the difference of time between the two impressions is greater or less than the limit of perceptibility.

For speech Deschanel[1] gives one-tenth of a second as the time interval that must elapse between a direct and a reflected sound striking the ear, so as not to overlap. Bartlett[2] puts it at one-ninth of a second while Catchpool[3] gives one-thirty-third of a second but none offer experimental evidence to establish their assertions.

Thus it is seen that when a source located at O sends



a wave of sound to a reflector at C an ear at D will hear the direct sound along $\overline{OD}$ and a reflected sound, the echo,

1 - Nat. Phil., Part IV, p. 24, 1900.
2 - Acoustics and Optics, p. 88, 1852.
3 - Sound, 4th Ed., p. 131, 1903.

coming from C. The time in seconds between these two sounds should not be less than the time in seconds $t = \frac{distance}{velocity}$

$$= \frac{(Oc + DC) - OD}{Vo\sqrt{1+\alpha t}} \qquad (1)$$

to give rise to a distinct echo, where $\overline{V}o$ is the velocity of sound in air at 0°C., α equal to 0.00366 and t the temperature. Thus giving the minimum time limit of perceptibility. Then the maximum space limit of perceptibility for an echo would be given by

$$S = T\ Vo\sqrt{1+\alpha t} \qquad (2)$$

where S is the space limit of perceptibility, or the path difference, which if exceeded by the difference between direct and reflected sounds will develop an echo. When the difference of routes exceeds this distance the interval between the two impressions upon the ear becomes distinctly perceptible, and in proportion as that difference becomes less than S, will the impression of the echo begin before that of the direct sound ends; and this overlapping, as it were, of impressions will give rise to reverberation. This will continue to a greater or less extent till the difference of routes becomes so small as to afford no sensible interval between the instances that mark the beginning of both impressions, in which case the echo will strengthen the effect of the direct sound.

Helmholz[1] has shown that in the octave b'''c'''', which gives 132 beats per second, that the ear still detected separate sounds, while R. Koenig[2] shows that for a lower pitch, 32 beats per second sufficed to produce an audible

1 - Sensations of Tone, 2 ed. p. 170, 1885.
2 - Quelques, Exp. d'Ac., p. 135, 1882.

sound resulting in UT_3.

The ear, tho a sensitive instrument, is not always trustworthy in its judgment of sounds. Experiments by Rayleigh[1] and L. T. More[2] show that the ear does not always detect the correct location of a sound. An efficient aid is given at this point by a consideration of the known action of light waves which are analogous to sound waves.

It is a well known fact that the laws of sound are analogous to those of light and that the fundamental laws involved in geometrical optics and the mathematical expression of these laws are also applicable to sound. It must be kept in mind, however, that sound waves are longitudinal compressional waves and require a material medium for their propagation, while light waves are transverse and do not require a material medium. Furthermore, sound waves are great in length compared with light waves, but travel at a very much slower rate.

R. W. Wood[3] not only used these similarities of the laws of sound and light in his discussions on reflection but actually photographed the sound waves to prove the analogy existing, while Rayleigh[4] has shown experimentally the analogy between sound and light waves.

Roughness or even corrugations do not effect the laws of reflection. This has been shown by Rayleigh[5] assuming the reflecting medium to be impenetrable. He shows that

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1 - Phil. Mag., 169, 456, 1877.
2 - Phil. Mag., 13, 452-459, 1907.
3 - Physical Optics, p. 44-50, 1905.
4 - Nature, 66, 42, 1902.
5 - Sound, Vol. II, p. 96.

however deep the corrugations may be if only they are periodic, and separated from each other by less than the wave-length of the vibration, the regular reflection is total. An extremely rough wall will thus reflect sound waves of moderate pitch as well as if it were theoretically smooth.

He further shows that whatever be the angle of incidence there are no reflected spectra (except of zero order) when the wave-length of the corrugation is less than half of that of the vibrations. Hence if the second medium be impenetrable, the regular reflection under this condition is total. As to the nature of the materials of which the walls are to be constructed and their absorbing power, one is led into a separate field of acoustics not intended to be included in this paper.

This subject has been treated experimentally by Sabine[1] and theoretically by W. S. Franklin[2] and Lord Rayleigh[3]. They show that the facility with which a body absorbs sound is inversely proportional to the amount it reflects. It is important to bear in mind that the loss of sound in a single reflection at a hard wall is very small, whether the wall be plane or curved.

If a plane wave of sound is normally incident to a concave surface it is reflected as a concave wave, concave in the direction of the point of reflection. And if we have a number of wave-fronts in different stages of reflection, it is apparent that the cusps trace a caustic surface as shown

1 - Eng. Rec., v. 41, 349, 1900.
2 - Phys. Rev., v. 37, 372, 1903.
3 - Sound, Vol. 2, 2d Ed. p. 311, 1896.

photographically by Wood[1]. It is evident that cusps thus generated from sound waves have the same intensity as the source, if the absorption is a minimum. That total reflection can take place from surfaces not theoretically smooth has already been shown.

An observer placed along the boundary of such a caustic will perceive an echo if the conditions of equation (1) for the limit of perceptibility are fulfilled. Thus we see that geometric solutions can be applied to acoustics if we keep in mind that a reflector whatever its shape can only act as such, if it is many times larger than the wave-length of the sound. It is evident then that reflectors for speech must have a diameter large in comparison to the waves developed. The mathematical relation that must exist has been developed by Rayleigh[2]. It follows that an observer may hear an echo so long as he is in the path of the reflected ray of sound and at the critical distance imposed by equation (1). But the unusually large diffractive properties of sound allows one to extend this region in proportion as the pitch[3] of the source decreases.

It then follows from the above discussion that an audience hall, which is to be free from echo, must have its walls and roof at such distances in relation to speaker and audience as determined by the limit of perceptibility. Neither should there be concave walls or ceilings whose cusps fall within this distance. If a concave surface is desired

1 - Phys. Optics, p. 44-55, 1905.
2 - Sound, 2d Ed., V. 2, p. 122-129.
3 - Rayleigh's Sound, 2d Ed., V. 2, p. 39.

it should be of such curvature that the principal focus does not lie within the building.

J. Henry[1] designed and supervised the construction of what he considered a perfect hall, acoustically, at the Smithsonian Institute. It seems that the is the only one who took into consideration, in a design, the limit of perceptibility which he determined roughly, since no data is given, at 30 feet, or about one sixteenth of a second.

The hall was so constructed that the walls behind the speaker were composed of lath and plaster and therefore have a tendency to give a more intense tho less prolonged sound than if of solid masonry. The sound directly from the voice and that from the reflection immediately behind the speaker is thrown forward upon the audience, and as the distance traveled by the two rays is much within the limit of perceptibility no confusion is produced by direct and reflected sound. No echo is given off from the ceiling since this is also within this limit.

S. Exner[2] also suggests plans for an echoless hall but omits dimensions. Blackall[3] gives some empirical reasons for dimensions. Besides these nothing definite exists on this subject, except occasionally one meets a general reference to the dimensions of a room, as follows: "It should have a definite proportion of the sides, like an organ pipe",

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1 - Ann. Rep. Smith. Inst., p. 221, 1856.
2 - Zeit. d. Ost. Ing. Arch. Ver., S. 141, 1905.
3 - Eng. Rec., 45, 541, 1902.
also Bul. Soc. d'En., 107, 571, 1905.

or, "that there should be no concave walls that concentrate the sound at a particular point".

Experimental Work

In order to test the acuteness of the writer's ears and also to verify the conflicting data on the limit of perceptibility, it was found advisable to determine this constant for a source of sound which was to be used in connection with the analysis of the echo in the Auditorium.

A blank wall, the stage wall of the Auditorium, was very well adapted to this work. A smooth close cropped grass surface stretches for several hundred feet from its base.

Stokes[1] has shown that for small distances wind has hardly any perceptible effect, the sound being propagated almost equally well in a direction contrary to the wind, but since the wind was imperceptible on the days of performing the experiments, its influence was negligible.

Considerable difficulty arose in interpreting the seemingly conflicting data obtained, until it was discovered that the echo observed in the experiments was due to sound reflected from a two foot cornice 50 feet from the ground rather than directly reflected sound. J. Henry[2] experienced the same difficulty while working on this topic and in order to avoid the difficulty he had constructed a perpendicular

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1 - B. A. Rep., p. 22, 1857.
2 - Ann. Rep. Smith. Inst., p. 221, 1856.

surface 12 feet square and from this more definite results were obtained. No such surface was available to the writer and the data given is taken from the Auditorium wall.

A metronome beating seconds, a telegraph sounder, and two blocks of wood when struck one upon the other were used as sources of sound.

The source was carried by the observer alternately towards and away from the wall until the echo was just perceptible. The source, the metronome or telegraph sounder, was also placed at distances of 25 feet and 50 feet from the wall and the observations repeated. By alternately retreating from and approaching the wall the observation error was reduced to a minimum. The differences in path thus obtained, or the limits of perceptibility, are indicated.

Telegraph Sounder

Distance of Source from wall D ft.	No Echo at D' ft.	Temp. t	Weight of Observation	Date	Lim. Per. S*
22.0	22.0	19°C.	10	May 7	109.0
25.0	14.5	22°C.	5	May 5	108.0
30.0	17.5	19°C.	10	May 7	117.5
40.0	23.5	19°C.	10	May 7	119.0
50.0	29.0	22°C.	3	May 5	128.0
			Average		115.0 ft.

* $S = TV_0\sqrt{1+\alpha t}$

Metranome

Source from wall D ft.	No Echo D' ft.	Temp t	Weight	Date	Lim. Per. S
33.0	33.0	60° F.	6	May -	119.0
36.5	36.5	18° C.	5	May -	124.0
36.0	36.0	18° C.	5	May -	123.0
36.0	36.0	15° C.	6	Apr. 23	123.0
25.0	18.0	18° C.	5	May -	109.0
30.0	17.5	19° C.	10	May 2	117.5
50.0	27.0	18° C.	5	May -	127.5
			Average		120.0 ft.

Blocks of Hard Wood

19.5	19.5	19° C.	5	May 7	107.5 ft.
18.0	18.0	13° C.	10	May 3	106.0 ft.

The disagreement of these results with those given by J. Henry can only be accounted for in assuming that the pitch of the instruments used were higher than those used by Henry, or that the echo which seemingly came from the cornice originated at some unknown surface. For trials made in the Auditorium a surface 30 feet away, the arch over the stage, reflected an echo quite perceptibly. This value is more in agreement with that of Henry. Unfortunately the early investigators omitted stating the pitch of their source which gave rise to the echo, thus affording one no basis of comparison.

The next step in the investigation was an application of the limit of perceptibility to the cause of echo in the Auditorium. With this in view it became necessary to locate the surfaces which generated the echo, and to get some idea of the reflecting possibilities that the Auditorium in question was addicted to.

The hall is a structure whose interior may roughly be described as a half of a hollow sphere whose center of curvature lies about 7 feet above the floor. It is 120 feet in diameter and has a seating capacity on the ground floor of 1190 chairs and in the balcony 905 chairs. A hard plaster on wire lath is used thruout the construction, forming an excellent reflector of sound. The stage, an open platform, extends well into the hall and has in the rear a blank wall, the lower half of which is coated with wood-sheathing. The plans show side arches, sections of spherical reflecting surfaces springing up from the balcony, whose centers of curvature lie in the center of the hall on a line with the balcony entrance. The rear arch in the balcony has the same curvature as the hall proper.

The glass sky-light in the center of the dome has a diameter of about 28 feet and communicates with the roof by means of a plastered well about 24 feet high.

The flooring and stage are constructed of hard wood, while the chairs are collapsible wooden opera seats; all good reflectors of sound.

The horizontal sections Fig. 1 and 2 are circles whose

circumferences if extended will have the stage wall for a tangent. By taking the sections as perfect circles and placing a source of sound on the stage at S, the usual place of a speaker's position, one can draw a curve thru the points of greatest intensity such that a caustic curve as shown in Fig. 5 is generated.

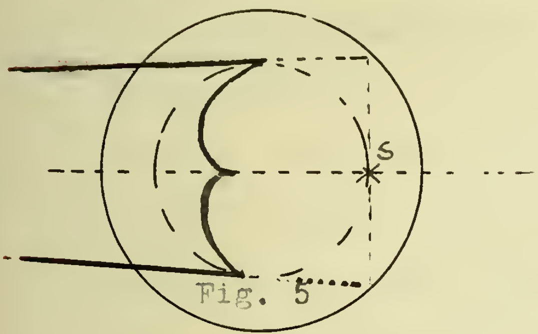

Fig. 5

Its general equation is given by Heath[1] as $\left[(4c^2-a^2)(x^2+y^2) - 2a^2cx - a^2c^2\right]^3 = 27\ a^4c^2y^2(x^2+y^2-c^2)^2$ for $c < a > 1/2a$, where a is the radius and c the distance of a source S from the center. To find the points of intersection with the reflector, make $x^2+y^2=a^2$ and the equation to the caustic becomes $(cx-a^2)^2\left[8a^2cx+a^4+18a^2c^2-27c^4\right]=0$ Hence the caustic touches the reflector at the points given by the equation, $cx=a^2$, which are the points of contact of the tangents drawn from the point S to the reflector if S be outside of the reflector, and are imaginary if this point be inside. The other point of intersection is determined by the equation $x = \dfrac{27c^4 - 18a^2c^2 - a^4}{8a^2c}$ This value of x is numerically less or greater than a, according as c is greater or less than a; this is according as the point S is outside or inside the reflecting circle.

Applying these conditions now to the Auditorium we would expect to find a maximum region of loudness at points corresponding to the cusps and edge of the caustic.

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1 - Heath's Geo. Op., p. 111.

Altho little reliance can be placed upon such a construction, as the author has been assured by the Department of Architecture, due to variation in construction from the plans given, yet it is of interest to see how near this geometrical construction is checked up by actual observation.

It is seen in Fig. 1 that the central cusp falls about in a position equivalent to the central aisle and first row of the balcony. This cusp also extends down into the lower floor. Here one would expect to find an unusual disturbance of some nature, which due to the refraction of sound should disappear at some distance under the balcony. Fig. 1 gives this curve with some points found by observation to possess characteristic disturbances. The arrowed circle indicates the direction of a region inclined at an angle of about 45 degrees as the direction of maximum intensity, while the circle with a cross in it indicates a region overhead as the angle of greatest intensity.

These positions were obtained by means of an ear trumpet and by using a metronome at S as a source of sound.

The nicety with which some of the areas thus obtained correspond to the construction is surprising. In this way it was discovered that what to the unaided ear sounded like a single echo, was in reality comprised of a number of echos coming from various surfaces.

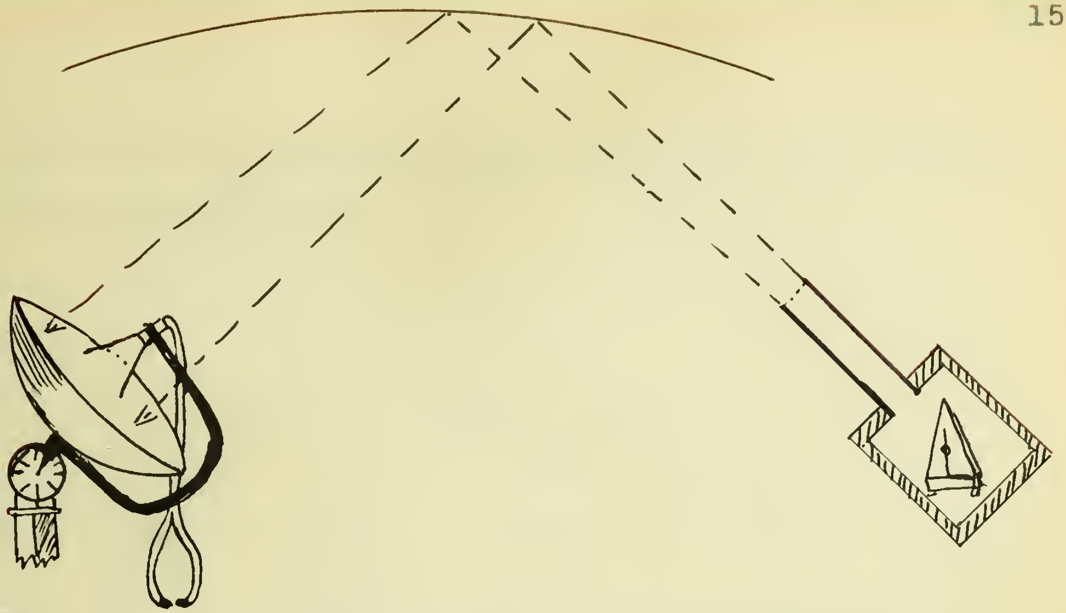
A phonograph record taken of a loud explosion on the stage reproduced an echo sounding like distant rumbling thunder.

After this general preliminary survey it became necessary to definitely locate the surfaces causing the echo.

It is a well known fact that sounds, especially of a grave tone, are very difficult to localize by the unaided ear. With this point in view most of the known methods of determining sound intensities were tried.

In many of the electrical methods[1] the telephone was reconstructed to attain a greater sensitiveness. The pressure controlling the intensity of the sound was increased to the maximum. An inconsistent deflection of several millimeters was all that was ever attainable. The same methods when applied to a smaller hall gave very satisfactory results. For the Auditorium these methods were not sensitive enough because it was necessary to use the apparatus at a distance of 80 feet from the source. The apparatus finally used was a concave spherical mirror with a radius of curvature of 30 cm. and a diameter of 49.5 cm. It was mounted on a stand which allowed the mirror to be rotated thru a vertical plane, the angle of rotation being read off on an attached protracter 7.5 cm. in diameter. The angles of the first quadrant were read as positive, those of the second, negative. At the principal focus and attached to the back of the mirror was mounted a conical resonator which could be connected with rubber tubing to both ears.

1 - J. F. von Hornstein, Beibl. Ann. d. Phys., 1902.
H. Setefanini, N. Cim., (3) 22, p. 97, 1887.
also Beibl. Ann. d. Phys., 1888.
G. W. Pierce, Pro. Am. Ac. Arts & Sc., (43) Feb. 1908.
Lord Rayleigh, Phil. Mag., (16) p. 244, 1908.
also Phil. Mag., May 1868.
Maxwell's Sci. Papers, Vol. 2, p. 121.



The reflector was set up at the points indicated in Fig. 3 and the angles observed thru which it was necessary to rotate the mirror to pass from a minimum intensity to a maximum and on to a minimum intensity of the echo under observation. That several echos had to be considered at some points becomes evident when we consider the varied reflecting surfaces involved. The angles of minimum intensity in all cases are positions of no echo. The angles of maximum intensity indicate the direction of echoes from the areas observed which had the greatest limit of perceptibility.

Observations were both made on a metranome and clock as sources of sound. They were placed in a thickly padded box communicating with the exterior thru a 25 cm. tin cylinder 12 cm. in diameter.

Since the pitch of both metranome and clock were high it is seen that a plane wave was generated since the diameter of the opening is greater than $1/2\,\lambda$ of the source.[1] In this way most of the diffraction effects accompanying these experiments were reduced to a minimum and this facilitated

1 - Rayleigh's Sound, Vol. 2, p. 38.

the localization of surfaces causing the echo, thus rendering the results more accurate.

Balcony

1st Row of Central Aisle — At Rail

Date	Min *	Max	Min	Source of Sound	Weight
Mar. 28	-51.0	-85.0	+79.0	Clock	5
Apr. 3	-50.0	+87.0	+75.0	C	1
Apr. 19	-51.0	+88.0	+74.0	C	10
Apr. 23	-54.0	-86.0	- -	Metro.	5
Apr. 25	-52.0	-84.0	+75.0	M	10
May 3	-50.0	-86.0	+70.0	M	2

4th Row Central Aisle 9 ft. from Rail

Apr. 10	-73.5	±90.0	+64.5	C	10
Apr. -	-69.0	-87.0	+70.0	M	5
Apr. 25	-62.0	+87.0	- -	M	5
Apr. 25	-62.0	-86.0	- -	M	5

A Second Echo

Apr. 10	-33.0	-46.0	-54.5	C	10
Apr. 25	-34.0	-43.0	-62.0	M	10

Central Aisle 23 ft. from Rail

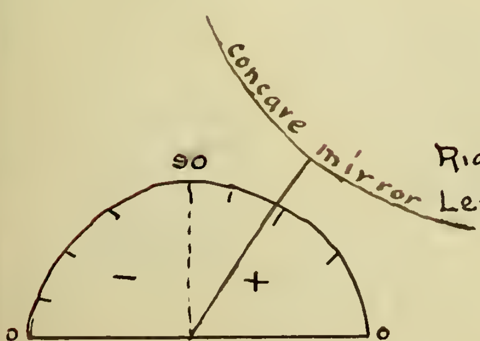
Apr. 10	+46.0	+31.5	+17.-	C	10

A Second Echo

Apr. 10	-85.5	+78.0	+60.0	C	10

A Third Echo

Apr. 25	- -	- 8.3	+82.0	M	10



Right hand quadrant readings are (+)
Left " " " " (−)

Lower Floor

39 Feet from Stage

Date	Min	Max	Min	Source	Weight
May 2	-55.0	+74.0	+64.5	M	10
Apr. 24	-52.0	-83.0	- -	M	10
Apr. 24	- -	+72.0	- -	M	2

28 Feet from Stage

Apr. 24	-27.0	-75.0	+66.0	M	10

A Second Echo

Apr. 24	- -	-36.0	- -	M	10

2 Feet from Stage

Apr. 24	+62.0	+35.0	+17.0-	M	5

A Second Echo

Apr. 24	-10.0	-58.0	- -	M	10

A Third Echo

Apr. 24	- -	+63.0	- -	M	5

On Stage

At Rear Wall

Date	Min	Max	Min	Source	Weight
Apr. 1	-73.0	- ? -	+87.0	M	3
Apr. 1	- -	-56.0	± 90.0	M	3

A Second Echo

Apr. 24	- -	-45.0	- -	M	10

A Third Echo

Apr. 24	- -	-32.0	- -	M	5

10 Feet from Wall

Apr. 24	- -	-41.0	- -	M	10

At end of paper

Fig. 3 shows the above data plotted for a source of sound placed at S and inclined at 45 with the horizontal. From this it is at once seen that all maxima point toward two areas: one the glass sky-light in the center of the dome and to the arch over the balcony, while the other area is located in the upper part of the rear arch of the balcony.

Starting at S and drawing a straight line to any point of maximum intensity and then down to the observer, it is found that in all cases the difference in path between direct and reflected sound vary from 60 to 100 feet. On the assumption that the path taken is the shortest one, which in some cases is not true because the sound may reach these surfaces and then the observer from the reflections of other areas, it is evident that in every case these surfaces lie outside the limit of perceptibility of 30 feet as found by Henry.

It does not follow since most of the reflecting surfaces are concave and generate foci lying within the Auditorium t that echoes are thereby generated. If these walls lie within the limit of perceptibility regions of loudness are created thru the reinforcement of the waves by reflection, thus giving rise to a confusion of sounds but to no echo.

Many remedies naturally suggest themselves, many of which have been found worthless but the most important of which may be classified as follows:

1. Stretching of wires and netting between source and reflecting surfaces.

2. Sounding boards.

3. Absorbing wall coverings.

4. Currents of air.

5. The application of the law of limit of perceptibility.

Of these cures the layman always suggests stretched wires to "break up the echo". But all cases that have come under the writer's observation have shown that the echo still persists. Upon inquiry it was found that the echo in every case had never been diminished thru their introduction. No effect could have been expected from the arbitrary way in which material, diameter, and tension of the wires were used.

That no possible dampening effect can result for sound waves from four to twelve feet in diameter, as are generated by the human voice, is shown by Rayleigh.[1] That only little obstruction takes place for very shrill sounds was shown experimentally by Tyndall.[2]

The same objection applies to netting. A cure by the introduction of netting into the dome of Dr. Parkhurst's Church in New York City, was claimed to have given satisfactory results. Professor Watson of the Physics Department who visited the church was satisfied that a very pronounced echo still existed. Upon inquiry it was also found that the netting had shown very little if any effect on the echo.

Wood partitions or obstructions, falsely classed as sounding boards, seem to be of value at first sight.

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1 - Sound, V. 2, p. 311.
2 - Tyndall's Sound.

These reflectors have often been used with questionable success, when placed above or behind the speaker.

A satisfactory explanation of their action has never been given, yet the question naturally arises whether it is possible to bring a ceiling or wall within the limit of perceptibility by means of such a reflector.

A simple calculation[1] will show that for $\lambda = 4$ feet, which are waves issuing from a high voice, it would require a circular reflector 31 feet in diameter to produce a sound shadow at a point six feet from the center. Due to the unusually large diffraction effect of sound, the area covered at a distance of three feet from the rear face would be inappreciable in proportion to the total reflecting areas remaining in a large audience hall. It becomes evident that even a large obstacle would have little or no effect in reducing the limit of perceptibility of space by its introduction.

Reflectors which were used for the above purpose were examined in many churches in which the roofs were very high, and in a few cases it was found that they were of more value in partially directing the sound to a certain portion of the room than in curing the room of echoes, because most of them were either placed above or in back of the speaker. Their efficiency must have been very low, since nearly all those seen in use were less than twenty feet in diameter. Yet a reflector may be placed in such a position in back of the speaker, if the reflector is the rear wall, so as to

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1 - Rayleigh's Sound, Vol. 2, p. 20.

partially shield reflecting surfaces which would cause echo. This shielding effect would be very slight, due to the unusual defractive property of sound.

The idea of curing echo by wall coverings which have a high coefficient of absorption for sound has given some very good results.

One case that came under the author's observation was the Auditorium at the University of Cincinnati. The hall seats about 500 and is rectangular in shape. It had an echo, observed as one walked up the central aisle. Professor More of their Physics Department hung some heavy curtains on the rear walls of both stage and auditorium, and also covered the front wall with curtains draped from the ceiling. No measurements on the duration of reverberation were made, neither were the surfaces causing the echo located. The author was convinced of the effectiveness of the cure of the echo, altho the hall suffered somewhat in its resonant qualities. A low tone spoken at the rear wall of the stage with the speaker's back to the audience could be distinctly heard at the farther end of the hall.

In this case curtaining the walls reduced the reverberation and indirectly absorbed the echo.

The question of reverberation in halls and the absorption of sound by porous material has been experimentally studied by W. C. Sabine[1]. He shows that absorbing material, when introduced into a hall, cut down the time of reverberation of the sound in accordance with the equation

1 - W. C. Sabine, Amer. Acad. Proc., XLII, No. 2, p. 51,1896.

$t = \frac{0.162\,\overline{V}}{\Sigma a S}$ where $\overline{V}$ is the volume of the room, "a" the absorption coefficient of the material used and material already in the building, and S the area of this material; while Rayleigh[1] and W. S. Franklin[2] treat the subject from a theoretical point of view.

W. W. Jacques[3], in curing the defects existing in the acoustics of the Baltimore Academy of Music, seating 1600, used a comparatively steady current of air which was sent from the back of the stage into the top of the gallery, the velocity of exhaust being about 15,000 feet per minute. No echo seemingly existed in the hall, since the author only gives data on the hearing properties which were greatly increased. Tyndall[4] attacked the problem of reflection of sound from various kinds of strata of air when at rest, and shows that the reflection, if any, is very slight; while Rayleigh[5] shows that for strata of such variable densities as hydrogen and air only 1/3 of the energy is reflected. It must be remembered that in practice the transition from one strata of things to the other would be gradual, and not abrupt as the above calculations imply. If the space occupied by the transition amount to a considerable fraction of a wave-length, the reflection would be materially lessened.

J. Henry[6], in his researches on fog signals, shows that

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1 - Sound, V. 2, p. 333.
2 - Phys. Review, p. 372, June 1903.
3 - Phil. Mag., V. 7, p. 111, 1879.
4 - Tyndall's Sound, 3d Ed., p. 282, 1875.
5 - Sound, Vol. 2, p. 82-84.
6 - Ann. Rep. Smith. Inst., p. 455, 1878.

a wind of 7.8 miles per hour accompanied a reduction of penetrating power of sound about 50%. It is thus seen that Jacques attained the desired reflection thru the motion of his air column, thus creating a new ceiling with intrinsic reflecting power. Since the current crossed the hall from stage to top of gallery, the sound waves would also have been bent down, as was shown by Reynolds[1] and Henry[2], so that the intensity is decreased above and increased proportionally below; thus allowing him to reinforce the sound at places where hearing was difficult.

Very little work has been done on this phase of the subject, but the writer hopes to study the reflecting power of a current of air in relation to its temperature, humidity, and velocity.

To bring the reflecting surfaces of a poor hall within the limit of perceptibility would necessitate the reconstruction of the walls and ceiling. This being hardly possible in most cases, it can only be effectively applied to the design of new halls.

The cure for the Auditorium under consideration, that suggests itself first, involves the introduction of enough absorbing material to reduce a possible reverberation and thus absorb the echo with it.

Sabine's[3] method was used to determine the time of reverberation in the hall and it was found to equal 5.8 sec. for an organ pipe n=450 blown with a constant pressure equal

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1 -Proc. R. S., 22, 531, 1874.
2 - Ann. Rep. Smith. Inst., p. 455, 1878.
3 - Eng. Rec., Ap. 1900.

to 12 cm. of water. Now applying Sabine's equation

$$t = \frac{0.162V}{\Sigma aS}$$

it was found that 4200 square meters of carpet must be used, whose α=.2, to reduce the reverberation to two seconds, when the hall was full of people. The impossibility of such an undertaking is quite evident.

It was observed that no echo existed under the balcony except that due to diffractive effects which is shown in the Figure. It then suggested itself that if a corresponding false gallery were built over the present balcony and provided with sufficient absorbing material that the present echo disturbing the balcony could be removed. But this construction does not relieve the lower floor of its disturbance.

The previous experiments show that the glass dome, the arch over the balcony, and the recess at the rear of the balcony are sources of acoustical disturbance. If these could be padded or remodeled, it would give better acoustics. It would also be desirable to cover the wall in the rear of the stage with an absorbent material. However, a final suggestion for cure involves other factors and further experimental work, and would therefore be premature in this discussion.

Thus it has been shown that in order to avoid echo in large audience halls, all reflecting surfaces should be placed within the limit of perceptibility; that structure of the walls should consist of a good absorber of sound; niches, reflectors and corrugations on the walls are ineffective as

obstacles to disperse the sound while wires and nettings have only a fictitious value; the value of currents of air is still an open question, while the placing of padding and curtains on walls and ceiling can only be applied to smaller halls.

In conclusion I wish to thank Professor Carman for proposing the problem and for his interest shown.

I wish also to thank Assistant Professor Watson for his valuable advice at all times freely given and for his cooperation and kind assistance.

Laboratory of Physics,
University of Illinois,
May, 1909.

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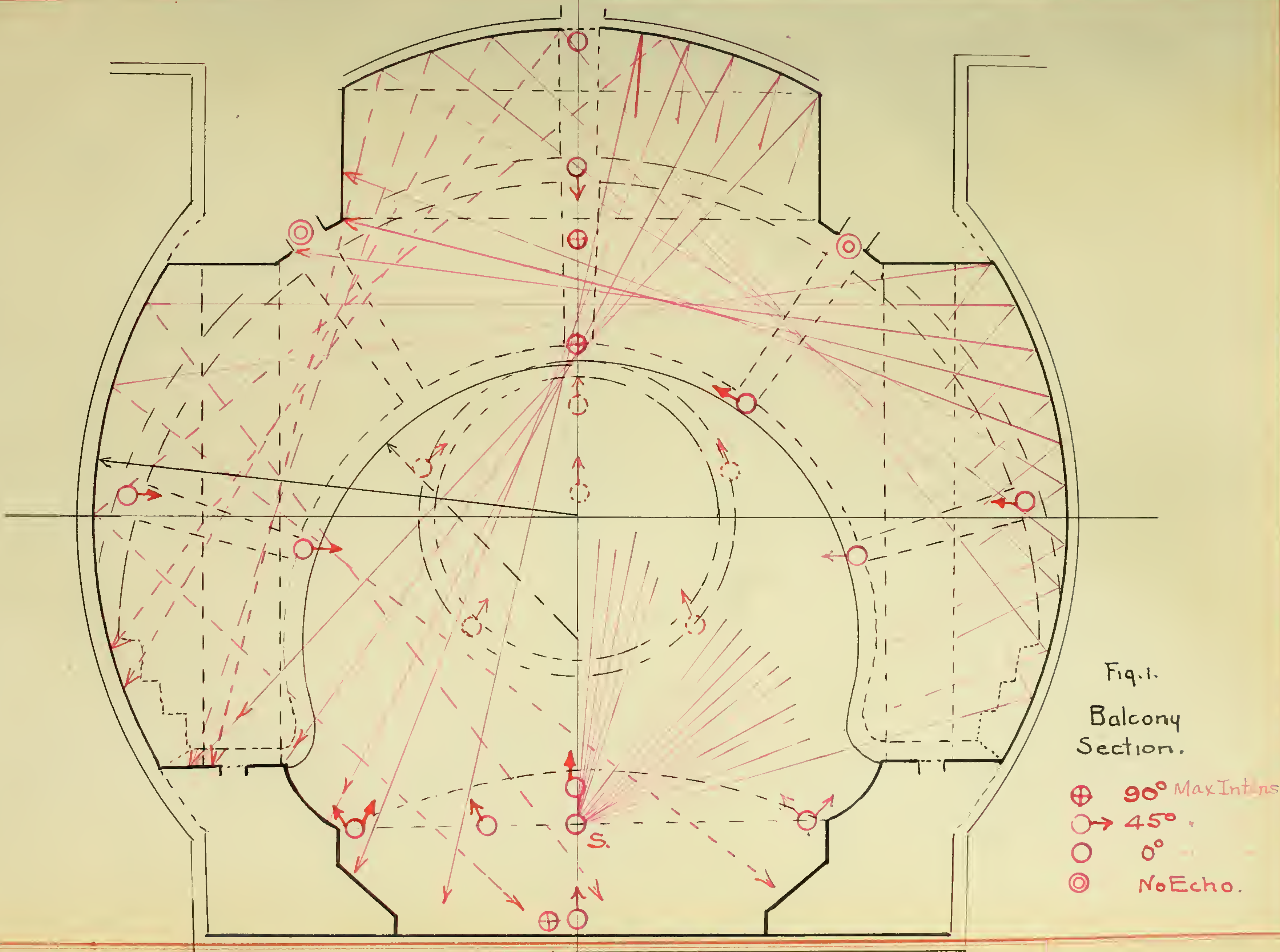


Fig. 1.

Balcony Section.

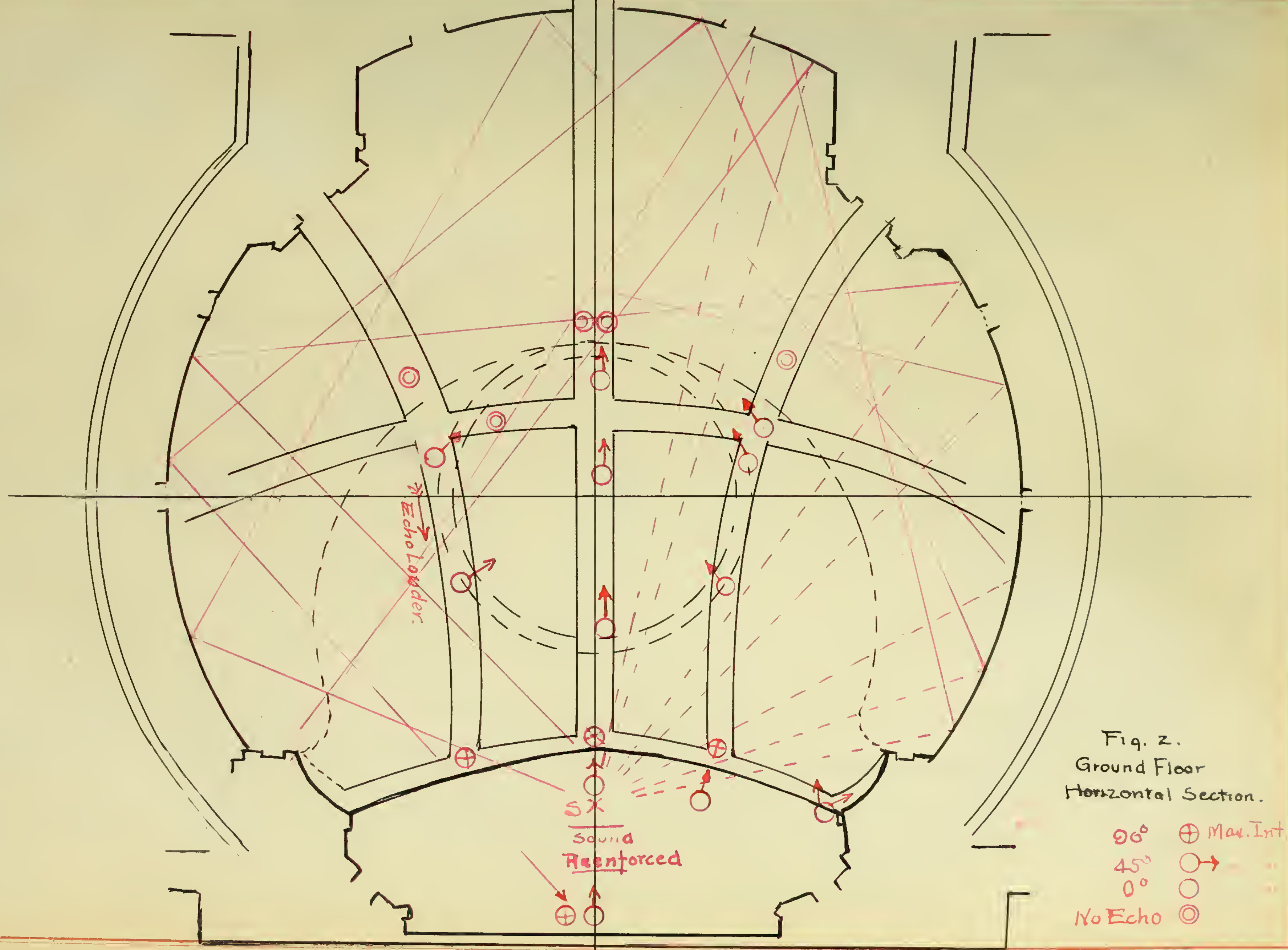
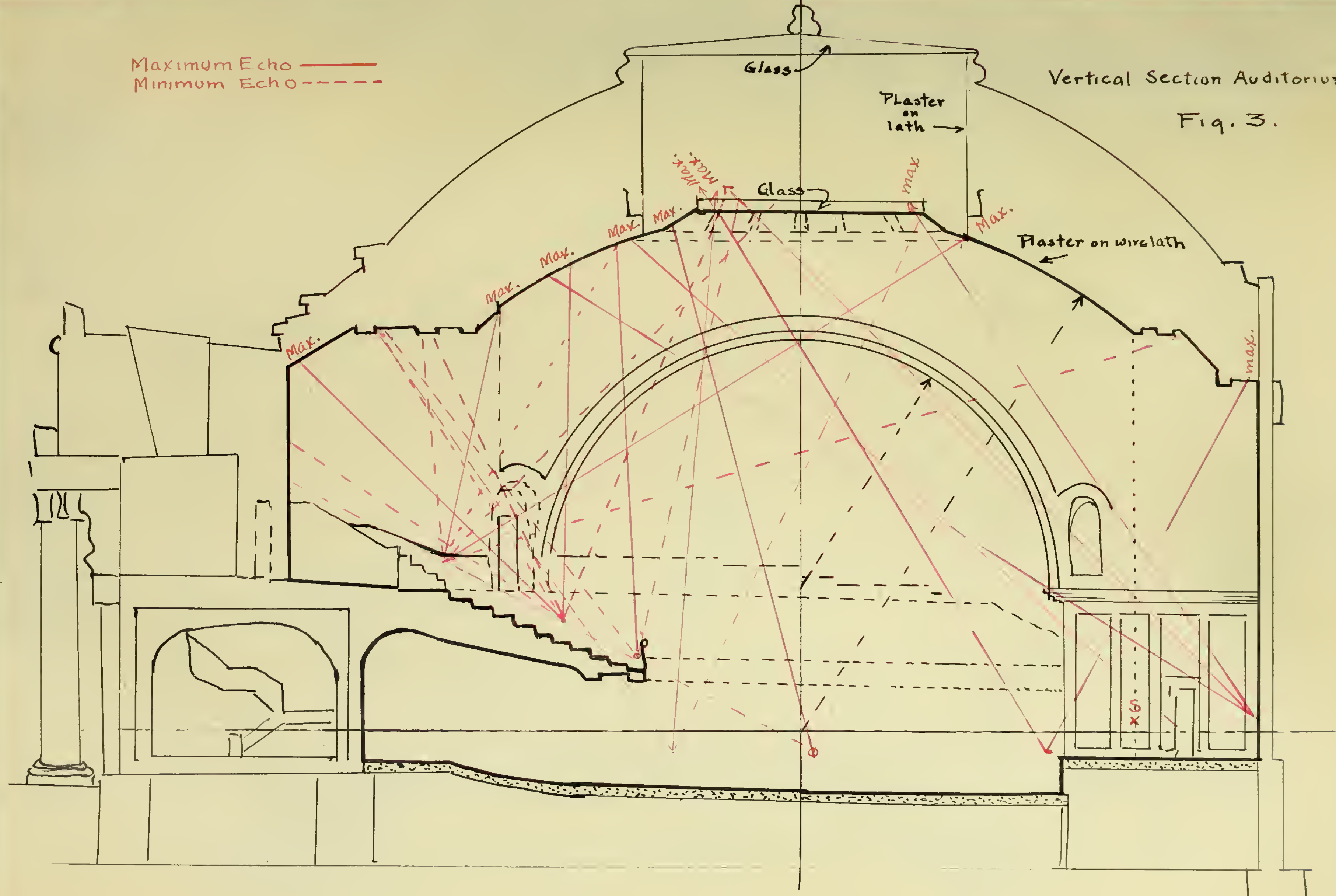


Fig. 2.
Ground Floor
Horizontal Section.

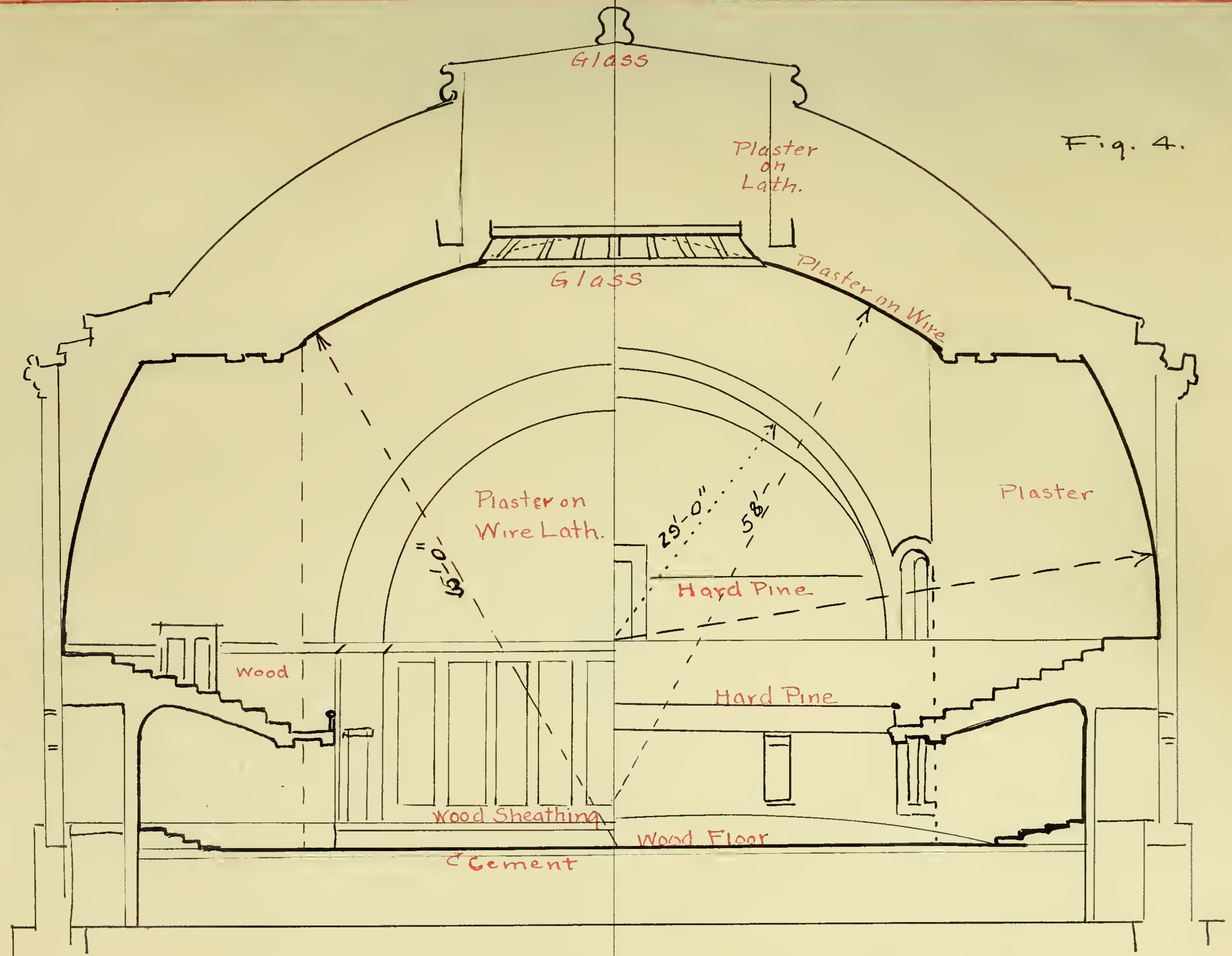
Vertical Section Auditorium.

Fig. 3.



Position of disturbing surface causing Echo from data.

Fig. 4.



Glass
Plaster
on
Lath.
Glass
Plaster on Wire
Plaster on
Wire Lath.
29'-0"
58'
63'-0"
Plaster
Hard Pine
Wood
Hard Pine
Wood Sheathing
Wood Floor
& Cement